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Modeling the time-dependent effect of the Ebbinghaus illusion on grasping

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Abstract—Various authors have reported a small but consistent effect of the Ebbinghaus illusion on the maximum opening of the hand during prehension. This effect has been interpreted in various ways. In the present study, we focus on the time-course of the effect of contextual elements on grasping. The analysis presented here is based on a model for the control of the digits that uses two movement parameters (the approach parameter and the intended contact positions). These two parameters are based on different spatial attributes (flanker-target distance and target-edge position). As we assume that the perception of both attributes is veridical, there is no need for on-line corrections in the model. We show that this model predicts all time-dependent effects of the Ebbinghaus display on grasping. Human behavior can show a reduction in context effects over time without assuming an underlying shift from illusory towards veridical size information.

Keywords: Prehension; motor control; illusion; size; smooth movement.

INTRODUCTION

Aglioti *et al.* (1995) conducted a very influential experiment on the effect of the Ebbinghaus illusion on grip formation during prehension. Their experiment showed that this illusion influences the maximum grip aperture (i.e. the maximum distance between the thumb and forefinger) in grasping much less than would be expected on the basis of the illusion's effect on perceptual judgements. This has caused a wealth of studies debating whether perception and action in healthy subjects use the same visual information (see for instance Smeets and Brenner, 1995, 2001a, c; Brenner and Smeets, 1996; Michaels, 2000; Carey, 2001; Glover and Dixon, 2001a; Plodowski and Jackson, 2001; Smeets *et al.*, 2002).

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Several explanations have been offered for the small but persistent effect of the Ebbinghaus illusion on maximum grip aperture. At one extreme, some authors (Pavani *et al.*, 1999; Franz *et al.*, 2000) have shown that this effect is equal to the perceptual effect if the latter is assessed using another display. At the other extreme, Haffenden and colleagues (Haffenden and Goodale, 2000; Haffenden *et al.*, 2001) have argued that the effect of the display on grasping was not due to the illusion itself, but to the circles in the annuli of the Ebbinghaus illusion acting as obstacles. A possible way to resolve this discrepancy is to look at more aspects of the prehension movement than only the maximum grip aperture (Glover and Dixon, 2001a). Glover and Dixon showed that the effect of the Ebbinghaus illusion on grip aperture decreases gradually during a movement (Glover and Dixon, 2002). They argued that the illusion affected the planning of movements, but not their on-line control. Their argument has been disputed by Danckert *et al.* (2002), who compared the effect of the illusion at maximum grip aperture with that at three instants before the time of maximum grip aperture. Danckert *et al.* (2002) reported that the effect of the illusion was smaller at these instants than at the time of maximum grip aperture.

In order to quantify the context-induced illusory changes in size, Glover and Dixon (2002) assumed that the influence of the contextual elements of the illusion was comparable to a change in object size. They therefore quantified the influence of the illusion on grip aperture by finding the change in object size that would have the same influence on grip aperture. However, if the context's influence on the grip aperture is not completely equivalent to that of a change in size, the resulting 'Scaled Illusion Effect' is not a good measure of the illusory change in size. This is so if the contextual elements are considered to be obstacles (Haffenden and Goodale, 2000; Haffenden *et al.*, 2001). In that case, quantifying the influence of the illusion at different times during the prehension movement requires a model that incorporates the influence of obstacles.

Recently, a formal, very simple model has been developed to describe the control of grasping (Smeets and Brenner, 1999, 2001b). In this digit control model, each digit moves as smoothly as possible to an appropriate contact position on the object. The surface at that position is approached more or less orthogonally. For each digit there are two parameters that represent the (visual) information used. One parameter is the above-mentioned contact position, which is the perceived position on the object's edge that is considered to be appropriate for contacting the object. The other parameter (approach parameter) determines the amount of the trajectory that is more or less perpendicular to the object's surface. The approach parameter captures all (visual and non-visual) task-variables that influence the required accuracy. The larger the chance that the movement will fail, the larger the approach parameter. Both these parameters influence maximum grip aperture. As perception of the object's size does not play a role in the digit control model, Smeets and Brenner (1999) argued that illusions of size will not directly affect grip aperture. They suggested instead that a small effect on grip aperture might be caused by a misperception of the contact position. If so, the influence of the display would be completely equivalent to a change in size, which is apparently not the case (Glover and Dixon, 2002).

The aim of the present paper is to try to examine whether the small effect of the Ebbinghaus illusion on maximum grip aperture could be related to its influence on the judgements of the required accuracy of the digits' movements. This is closely related to the suggested role of the annuli in the display as obstacles for the digits (Haffenden and Goodale, 2000; Haffenden *et al.*, 2001). The behavioral effects of obstacles on prehension consist of changing both grip aperture and movement speed in a way that depends on the exact location of the obstacles (Tresilian, 1998; Mon-Williams and McIntosh, 2000; Mon-Williams *et al.*, 2001). The change in movement speed indicates that not only the constraints on the digits' average paths are changed, but also the accuracy constraints (Fitts, 1954; Fitts and Peterson, 1964). In terms of the model, this means that the approach parameter will have changed.

In the rest of the paper we will assume that all changes in grip aperture that are caused by the Ebbinghaus illusion are due to an increase in the judged accuracy requirements. If so, similar effects should be found by increasing the approach parameter in the digit control model (Smeets and Brenner, 1999). By analyzing model movements we will examine whether this can explain the apparently contradictory experimental results found by Danckert *et al.* (2002) and Glover and Dixon (2002). Subsequently, we will re-analyze the data of Glover and Dixon (2002) to test whether other parameters of the movement also follow the predictions.

MODEL PREDICTIONS

To model the experiment of Glover and Dixon (2002) we used the model approach as outlined by Smeets and Brenner (1999, 2001b). In this approach, we model movements of the individual digits as maximally smooth movements that approach the surface more or less perpendicularly. How much of the trajectory is more or less perpendicular to the object's surface is determined by the approach parameter. This parameter can be estimated from the maximum grip aperture (see end of this section). As the digits were initially in contact with a 1 cm diameter cylinder in Glover and Dixon's (2002) experiments, we used the equations for the maximum grip aperture that take the initial aperture into account (Smeets and Brenner, 2002). The digit's contact positions appear in this equation as the object's diameter d. The approach parameter is indicated by a_p. If grasping starts with an initial hand aperture d_0, the model predicts that the grip should evolve as a function of relative time t_r ($t_r = 0$ is movement onset; $t_r = 1$ is the end of the movement):

$$grip(t_r) = d_0 + \big(a_p(t_r - 1)^2 + (d - d_0)\big(6t_r^2 - 15t_r + 10\big)\big)t_r^3. \tag{1}$$

The effects of changing object size and approach parameter are illustrated with an example in Fig. 1a. A 1 mm change in object size d results in a monotonic increase in additional grip aperture from zero at movement onset to 1 mm at contact (dashed

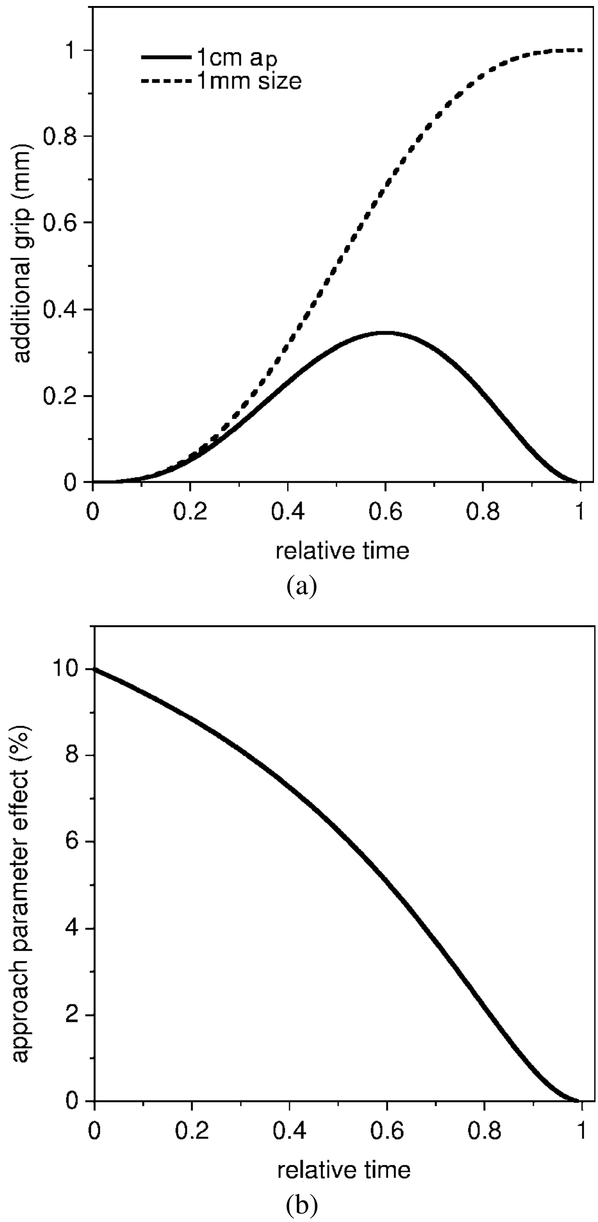


Figure 1. Model predictions. Comparison of the predicted additional grip aperture caused by a 1cm increase in approach parameter with that caused by a 1 mm increase in object size. (a) The changes in additional grip aperture as a function of time. The maximum effect of an increase in approach parameter is found at a relative time of 0.6, slightly before the moment that maximum grip aperture is reached. (b) The effect on grip aperture of an increase in approach parameter relative to that of an increase in object size, expressed as a percentage of the ratio $\Delta a_p / \Delta d$ (equation (2)).

line in Fig. 1a). For a 1 cm increase in approach parameter a_p (continuous line in Fig. 1a), the model predicts a gradual increase of the additional grip aperture peaking at 0.3456 mm at $t_r = 0.6$, slightly before the time of maximum grip aperture. Thereafter the effect reduces to zero at the end of the movement, when the object is contacted. Note that both object size d and approach parameter a_p are linear terms in equation (1), so the effect on grip aperture of changing object size or approach parameter (at a certain relative time in the movement) is independent of the values of the parameters themselves. This does not hold for the maximum grip aperture (discussed later in this section), because the moment of maximum grip aperture depends on the approach parameter and object size.

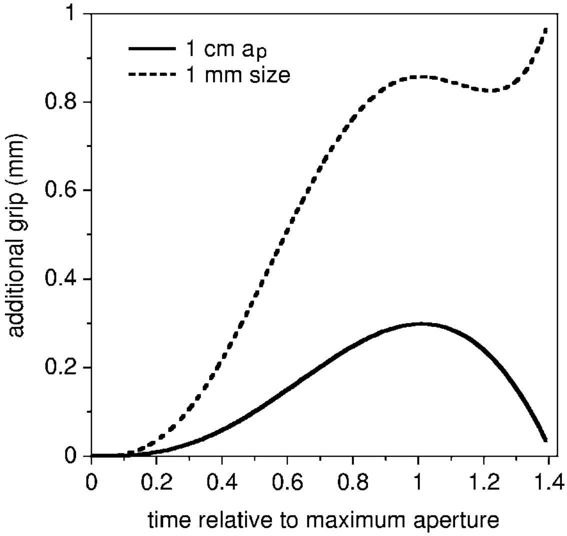
To obtain an equivalent of the 'Scaled Illusion Effect' as used by Glover and Dixon (2002), we divided the predicted change in grip aperture when changing the approach parameter (Δa_p) by that predicted for a change in object diameter (Δd):

$$\frac{\Delta(a_p) \rightarrow \Delta grip(t_r)}{\Delta(d) \rightarrow \Delta grip(t_r)} = \frac{(t_r - 1)^2}{(6t_r^2 - 15t_r + 10)} \frac{\Delta a_p}{\Delta d}. \tag{2}$$

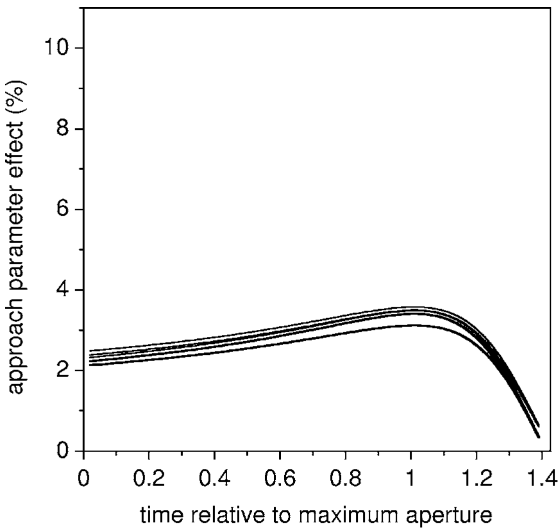
From this equation we can see that the relative effect of obstacles reduces gradually from $0.1\Delta a_p/\Delta d$ at $t_r = 0$ to 0 at $t_r = 1$. This is illustrated in Fig. 1b.

In the analysis above, the movements were scaled relative to the total movement time. If one scales the timing of the grip aperture traces relative to the time to maximum grip aperture before determining the illusion effects (as done by Danckert *et al.*, 2002), the model predicts a different pattern of results. In that case, the equations for the effect of a change of approach parameter, expressed as a fraction of the effect of a real object change, are no longer independent of the values of a_p and d. We therefore restrict ourselves to some numerical examples of the predicted behavior. Due to the re-scaling of the time-axes, a 1 mm increase in object size, in general, does not lead to a monotonic increase in additional grip aperture (see dashed curve in Fig. 2a). Furthermore, the maximal effect of a change in the approach parameter is now at exactly the time of maximum grip aperture, instead of just before it. As the approach parameter effect depends on the amplitude of the perturbations used to calculate it, we give some examples based on various numerical comparisons in Fig. 2b (the curve in Fig. 1b is independent of the values used for the change in approach parameter and object size). The resulting time course of the effect of the illusion differs dramatically from that in Fig. 1b. Moreover, in the initial part of the movement the illusion seems four times less effective when expressed in this manner. This seemingly unimportant change in the way in which trials are synchronized therefore has quite a dramatic impact on the apparent magnitude of the illusion effect on grasping.

The main reason for the dramatic difference between scaling relative to movement time (Fig. 1) and relative to time to maximum aperture (Fig. 2) is that in our model the time of maximum grip aperture depends in opposite ways on changes in size and accuracy constraints. If the maximum grip aperture is larger because the object is larger, the maximum aperture occurs later. If it is larger due to a larger approach



(a)



(b)

Figure 2. The same model as used in Fig. 1, analyzed in a slightly different way. We scaled the timing of the different conditions so as to synchronize the times of maximum grip aperture instead of the ends of the movements. (a) The additional grip aperture due to a 1 cm increase in approach parameter (continuous curve) peaks at exactly the time of maximum grip aperture. The additional grip aperture for a real change in object size (dashed curve) now shows a local maximum at the time of maximal grip aperture. (b) The effect of an increased approach parameter relative to that of an increase in object size expressed as a percentage of the ratio $\Delta a_p/\Delta d$. Because for this synchronization scheme the relations are non-linear, we calculated the effect for combinations of 1 –10 mm changes of object size and 1–10 cm changes in approach parameter. The reference condition is an object size of 3 cm and an approach parameter of 30 cm. The effect of the illusion appears to increase until the moment that the maximum grip aperture is reached.

parameter, it occurs earlier. The prediction according to Smeets and Brenner (2002) is that the grip opens to a maximum

$$grip_{\max} = d_0 + \left(\frac{3(a_p + 10(d - d_0))}{5(a_p + 6(d - d_0))}\right)^4 \left(\frac{4}{15}a_p + d - d_0\right), \tag{3}$$

at relative time t_r

$$t_r = \frac{3(a_p + 10(d - d_0))}{5(a_p + 6(d - d_0))}. \tag{4}$$

In the next section, we will estimate the a_p from the maximum grip aperture in the experiment of Glover and Dixon (2002), and the change in a_p from the effect of the illusion on grip aperture in that experiment. We will then use the model to predict how the timing of the maximum grip aperture should have changed due to the illusion, and compare these predictions with their data.

COMPARISON WITH EXPERIMENTAL DATA

For the comparison, we reanalyzed the experimental data of Glover and Dixon (2002). Unless stated otherwise, data processing was the same as in the original paper. We started our analysis by determining the grip aperture for 20 steps of relative time. The original paper was based on two experiments. In the first experiment (11 subjects), there was one block of grasping trials. In the second experiment (15 subjects), there were two blocks of grasping trials, one with and one without visual feedback during a trial. Within a block, there was quite some variability between subjects, which made it difficult to accurately estimate the effect of the illusion. The subjects' behavior differed clearly between the two blocks of the second experiment (larger apertures in the no-vision condition). This difference is what our model predicts for such a manipulation, because the approach parameter will be larger in the no-vision condition to compensate for the lack of accuracy (Smeets and Brenner, 1999). However, as our predictions in Fig. 1 are independent of the value of the approach parameter, we decided to average the final results over all 41 subject-block combinations to obtain the best estimate of the shape of the curve. The onset of motion was defined as the point at which the thumb's speed exceeded 0.1 m/s. This is not the time of motion onset in our model. For a movement of 20 cm with a movement time of 740 ms, our model predicts that this threshold is reached at about 100 ms (varying slightly with the approach parameter), corresponding to 13.5% of the movement. To make the experimental traces comparable with those of the model, we scaled the experimental timing axis so that it ranges from 13.5 to 100%.

We started our comparison by subtracting the average grip aperture profiles for the illusory large conditions from those for the illusory small conditions. This was done for each subject-block combination, and the values were then averaged. The result is plotted as the continuous trace in Fig. 3a. The maximum of this difference was

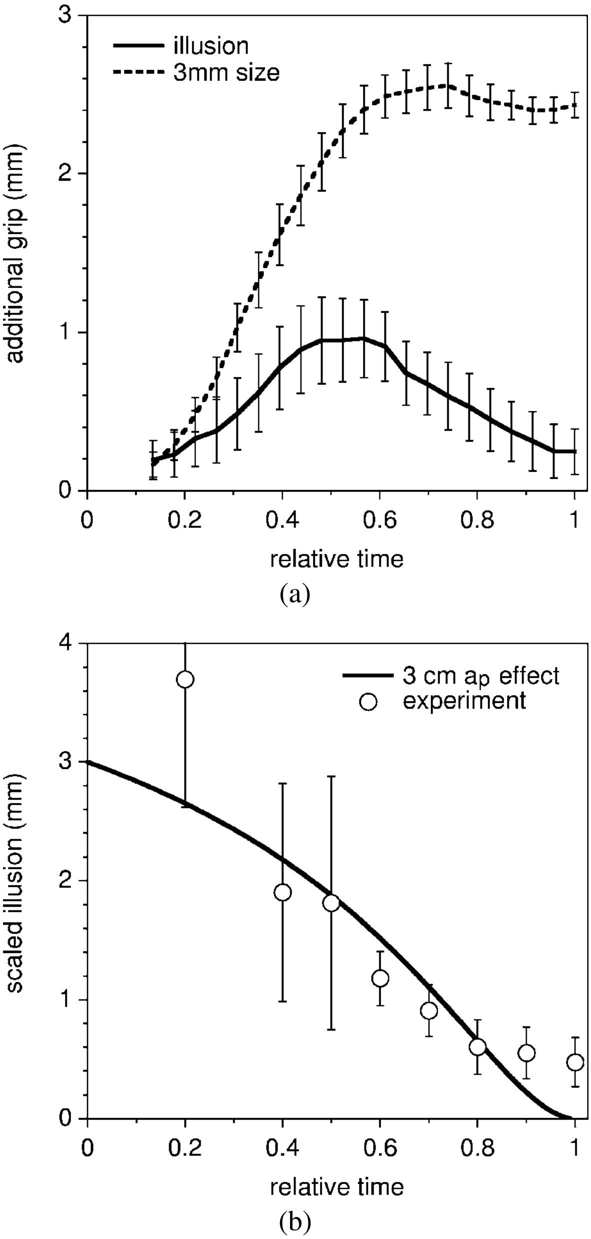


Figure 3. The experimental results of Glover and Dixon (2002). Error bars indicate the between subjects-block combination standard error of the mean. (a) Data plotted in the format of the model predictions in Fig. 1a. (b) Open circles: the magnitude of the illusion in the experiment expressed as the real change in size that would yield the same additional grip at that time. Continuous line: the model prediction for this measure if the additional grip is caused by a 3 cm increase in approach parameter.

0.96 mm at 57% of the movement. The timing of the maximal effect is thus close to the predicted $t_r = 0.6$ (Fig. 1a). Comparing the continuous trace in Fig. 3a with the corresponding trace in Fig. 1a, we see that the observed maximal effect is three times as large as the effect predicted for a 1 cm increase in the approach parameter. We can therefore interpret the effect of the illusion on grasping as a 3 cm increase in the approach parameter. As the approach parameter increase is three times larger than that used for Fig. 1a, we also plot in Fig. 3a the experimental effect of a three times larger (3 mm) increase in object size. This effect was obtained by fitting a line to the grip aperture as a function of object size for each time-point, and using the slope to predict the effect of a 3 mm increase in size. Again the model corresponds reasonably well with the experiments (dashed curves in Fig. 1a and Fig. 3a).

If one hypothesizes that the effect of the Ebbinghaus illusion on grip aperture is caused by a change in perceived size, the best way to present experimental data is as the ratio of the effect of the illusory size change to that of a real size change (Glover and Dixon, 2001a, b, 2002). We performed such an analysis in Fig. 3b. We calculated the ratio separately for each subject, condition and time-sample. As the size of the effect is small, we averaged the data not only over subjects and conditions, but also over time-samples. The variability was relatively high in the first part of the movement, so we averaged more time-samples for the first point. The resulting data points (open symbols) are reasonably close to our prediction (continuous line) that is based on the assumption that the difference between the two illusion conditions is caused exclusively by a 3 cm larger approach parameter.

The predictions shown in Fig. 2 are based on an analysis corresponding to that used by Danckert *et al.* (2002). The predicted increase of effect up to maximum grip aperture also corresponds to their experimental results that showed that the additional grip increased up to the time of maximum grip aperture. The apparent difference between Danckert *et al.*'s (2002) findings and those of Glover and Dixon (2002) can thus be explained by the differences in the way their data were analyzed.

The last comparison that we will make is for the timing of the maximum grip aperture. To make predictions for this parameter using equation (4), we need an estimate of the approach parameter a_p, which we will base on equation (3). The maximum grip aperture is the maximum distance between the contact surfaces of the digits, which is smaller than the maximum distance between the markers on the digits. In the experiment of Glover and Dixon (2002), the object size d was about 3 cm, and the maximum grip aperture was about 0.6 cm larger than the final grip aperture. We therefore estimated the maximum grip aperture to be 3.6 cm. This yields $a_p = 30$ cm, for which we show the predictions in Fig. 4a. The maximum grip aperture will occur at $t_r = 0.714$. If, due to the different context, the approach parameter increases by 3 cm, the peak aperture will occur 0.7% of the movement time *earlier*. However, if the object's size increases by 3 mm (leading to the same change in maximum aperture), the peak aperture will occur 1.4% of the movement time *later*. The predicted differences are small (about 1% of the movement time), and thus would not necessarily be statistically significant in experimental data. The

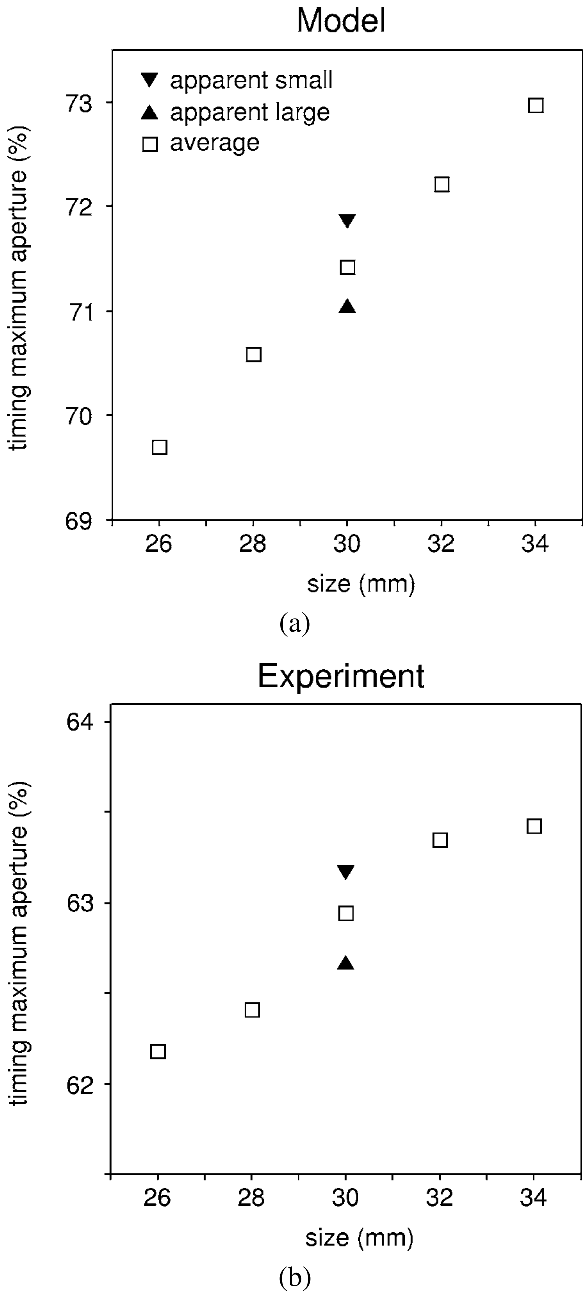


Figure 4. The timing of maximum grip aperture. Open squares indicate the average effect of object size; filled triangles indicate the effect of the illusion. (a) Model predictions in which the illusion is modeled as a 3 cm difference in approach parameter. (b) Experimental data.

fact that Danckert *et al.* (2002) did not find a statistically significant difference in timing of peak aperture between conditions is thus not in conflict with our predictions.

To make an accurate estimate of the time of maximum grip aperture in the experiment of Glover and Dixon (2002), we fitted a second order polynomial through the grip apertures curves (averaged over subjects and blocks) between 35% and 80% of the movement time. The polynomial fits the data very well ($r^2 > 0.99$). The location of the peak of this polynomial is a good estimate of the time of maximum grip aperture. The pattern of results (Fig. 4b) corresponds very well to the model predictions (Fig. 4a). The differences between the two context conditions were predicted very well, only the absolute timing of peak aperture was far from perfect. As predicted by our model, the (larger) maximum grip aperture occured *later* when the object was larger. The most important experimental result is that, as predicted for a larger approach parameter as the source of the larger grip aperture, the maximum of grip aperture occurred *earlier* if the increase in aperture was caused by the context (0.5% of the movement time).

DISCUSSION

We attributed all effects of the Ebbinghaus illusion on grip aperture to changes in judged accuracy requirements. Implemented in our digit control model of grasping by an increase of the approach parameter (Smeets and Brenner, 1999), this predicted most of the results obtained by Glover and Dixon (2002). Although we could predict all effects of the illusion adequately (including those reported by Danckert *et al.*, 2002), the model did not capture two aspects of the data. One is the timing of maximum grip aperture (the different scales in Fig. 4a and b). The other is the effect of the context when contact is made (compare Fig. 1 and Fig. 3 at the end of the movement). In the experiment, the two illusion conditions do not end at the same grip aperture. As the physical size of the object did not differ between the conditions, this may have been caused by the fact that it was not the aperture between the digits but that between the markers that was measured. A different relative orientation of the digits (for example, one could grasp with the fingernails either perpendicular to the object's surface or parallel to it) could have caused a different marker-distance with the same digit distance. Another possibility is that the criteria used for movement offset (i.e. when velocity of the thumb decelerated to zero in the forward direction) was slightly before the forefinger had contacted the target, and thus slightly before the grasps were actually complete. The same arguments might explain why the final grip aperture for a 3 mm larger object was not 3 mm larger (dashed lines in Fig. 3a).

The basis for our modeling approach is the notion that we can perceive the veridical positions of the edges of objects, regardless of the size illusion (Smeets *et al.*, 2002). One could ask why this information is not driving our perception of object size. In our view, the reason is that for the on-line control of action we need information that can be available at short delay, such as egocentric positions (Brenner and Smeets, 2001). The reason that this information is not used to determine an object's size is that it is rather inaccurate at reaching distance: about 3–5 mm (van Beers *et al.*, 1998). This corresponds to an accuracy of about 5–7 mm in determining object size, about 20% of a typical 3-cm diameter target used in grasping research. Using additional information sources (such as retinal image size and disparity) will generally lead to a more accurate percept, even in the reduced environments typically used in perception research. For instance, for isolated targets of about 3 cm (viewed at 1–2 m), the Weber fraction for estimation of absolute size is about 6% (McKee and Welch, 1992). This more accurate information can in our view be used when the processing speed is not critical, for instance when making a perceptual judgement or when scaling forces to lift an object (Brenner and Smeets, 1996). That such judgements are prone to biases, such as the one caused by the Ebbinghaus illusion, is normally irrelevant because these biases are 1–2 mm (Franz, 2001), and thus within the limits of perceptual accuracy.

We implemented obstacle avoidance in our model by manipulating the approach parameter. We argued that the required accuracy determines this parameter. However, the approach parameter may also depend on the required force after contact. Size illusions are indeed known to influence the forces with which objects are lifted (Brenner and Smeets, 1996; Jackson and Shaw, 2000). However, the empirically observed relationship between the contact forces and the kinematics of grasping is not as clear as one would predict on the basis of this reasoning (Weir *et al.*, 1991; Smeets and Brenner, 1999). The analysis that we performed is independent of what induces the increase of approach parameter. However, an interpretation in terms of perceived mass predicts that the effect on grip aperture would be present for any size illusion, irrespective of the way the illusion is brought about. This is not so if the effect is brought about by considering the flankers as obstacles. In that case, the effect of the illusion on maximal grip aperture would be absent when the inducing structure cannot be regarded as an obstacle for normal grasping. The latter interpretation is supported by experimental results: there is no effect of a size illusion on maximum grip aperture if the contextual elements are far from the object (Hu and Goodale, 2000; Haffenden *et al.*, 2001).

Our model predicts that the absolute effect of the illusion will increase until 60% of the movement time (Fig. 1a). It also shows that the timing of the maximum aperture changes both with object size and required accuracy. The larger aperture occurs earlier if caused by a larger approach parameter, but it occurs later if caused by a larger object. This differential effect on the timing of the maximum grip aperture is one of the reasons that the scaled effect of the illusion decreases during the movement (Fig. 1b). At the same time, this difference in the timing is the reason that the scaled effect of the illusion increases until the time of maximum grip aperture, if that time is used as the reference point (Fig. 2b). If we apply this time-scaling (as done by Danckert *et al.*, 2002) to our model of the experiment of Glover and Dixon (continuous line in Fig. 3b), the scaled illusion would start at 0.7 mm just after movement onset, and increase to 1.0 mm at maximum grip aperture. Of course, the data-points would also change in a similar way due to the re-scaling. One therefore has to be very careful in analyzing data before claiming that the results do not support either our model or the original planning-control interpretation of Glover and Dixon (2001a, 2002).

As a last point, we will discuss the original hypothesis of Glover and Dixon (2001a, 2002). According to that hypothesis, contextual illusions affect the planning of movements more than their execution. Although this model adequately predicts a decrease of illusion effects over the course of a movement, the results of the present analysis show that this hypothesis is but one possible explanation for the decrease. The alternative presented here is only remotely comparable to the planning-control interpretation in that one of its parameters (the approach parameter) is more closely related to the planning than to the on-line control, whereas the other (the intended contact position) is more likely to be controlled continuously. The important difference is that these two parameters are based on different spatial attributes (flanker-target distance and target-edge position). As we assume that the perception of both attributes is veridical, there is no need for on-line corrections in the model. The present analysis shows that the digit hypothesis of grasping (Smeets and Brenner, 1999, 2001b) provides a very plausible explanation of the changing effects of the Ebbinghaus illusion over the course of a grasping movement, just as it had for the time-dependent effect of a simultaneous tilt illusion on grasping (Smeets *et al.*, 2002).

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